

NASA – JOHN F. KENNEDY SPACE CENTER – DYNAMIC ENVIRONMENTS, KSC LSP FLIGHT
ANALYSIS DIVISION

De-Trending Techniques

Methods for Cleaning Questionable Shock Data

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Introduction:

For engineers involved in high level pyrotechnic shock testing typically greater than 1000 Gs, ensuring the accuracy and validity of test results has always proven to be a difficult task. Given the same environment and initial conditions, pyrotechnic shock testing results can vary widely between facilities and in some cases from 30 – 200% [ref-1.1]. This can result in either an under-test condition where the Qualification requirements are not met, or an over-test condition which can add substantial damage or ultimately break the component.

In order to understand the true shock environment, we need a method for determining the true levels, or “Truth Data”. We also need to understand if test data is questionable, how can we correct or clean this data and get a more accurate picture of the true levels. We need a method to clean questionable data since in most cases, data is reviewed many months later after-the-fact and re-testing may be impractical, expensive and affect schedule. The main subject of this paper is a method I am going to present for De-trending or correcting shock data. We can use this method to pre-screen data for understanding the validity of test results and whether the data can be cleaned to represent a more accurate picture of the true results.

De-trending Criteria:

Before we can examine shock data and determine the true levels, we need a set of criteria from which we can screen the data. The IES “Handbook for Dynamic data Acquisition & Analysis, ver. 12.1” [ref – 1.2] identifies a number of rules for evaluating shock data including:

- Accelerometers should not be closer than 6 inches to pyrotechnic source.
- A zero shift in acceleration data may be an indication of invalid data or improper test setup.
- Velocity should not diverge to infinity, but rather oscillate around zero and dampen out.
- Displacement should not diverge to infinity.
- Acceleration-Time histories should be centered about zero and not exhibit noise spikes or zero shifts.
- Negative and Positive Shock Response Spectrums (SRS) should look similar.

The focus of the De-trending methods that will be discussed will be based on the Velocity and Displacement rules listed above where both Velocity and Displacement should not diverge to infinity but rather oscillate around zero and dampen out. As a result of this method, we will be able to screen shock data for zero shifts in acceleration and evaluate the overall quality of data. Before we start to discuss the Velocity De-Trending method, we should discuss various De-trending techniques and the methods used to clean and screen data.

De-trending Methods

Although there are various methods to clean and screen shock data, we will discuss four methods which include: Velocity and Displacement, Wavelet, Bandpass filter and Moving Average with Cspline fit. The Velocity and Displacement methods are applied by computing a Least Squares or Cspline fit of the single

or double integral of Acceleration-Time history. The result is then subtracted from the original acceleration-time history to produce the De-Trended result or normalized acceleration curve. For the Wavelet method, we use a Daubechies Order-coefficient wavelet filter to remove the highest and lowest frequency components of the signal. We then recombine the signal and form the De-trended result. For the Bandpass filter method, we simply employ a Bandpass filter such as (4-pole Butterworth) to remove the distorted portions of the signal. The signal is then reconstructed to form the De-trended result. For Moving Average with Cspline fit, a moving average is computed for the signal and then a Cspline fit is applied to the result to produce the De-trended curve. The quality of resulting data is then evaluated based on the rules and methods listed in the IES handbook. The focus of this paper will be on the Velocity method.

Velocity De-trending Method:

The Velocity method computes a velocity curve based on integrating the Acceleration-Time history and using a Least Squares or Cspline fit to approximate the Velocity curve. The Velocity curve is differentiated to compute acceleration and then subtracted from the original Acceleration-Time history. The De-trended Acceleration-Time history can be integrated again to compute velocity and then evaluated to determine the quality of De-Trending. The following represents a mathematical representation of the process:

$$v = \int a \cdot dt ; \quad (\text{eq. 1.1})$$

$$v' = \text{Least squares or Cspline fit of } v \text{ or the De - trended velocity;} \\ v = \text{velocity}; \quad a = \text{orig. accel.}$$

$$\frac{dv'}{dt} = a' ; \quad (\text{eq. 1.2})$$

$$a'' = a - a' ; \quad a' = \text{De - trended accel}; \quad a'' = \text{Normalized accel.}$$

$$v'' = \int a'' \cdot dt ; \quad (\text{eq. 1.3})$$

$$v'' \text{ is the Detrended velocity}$$

By examining the De-trended velocity, we can determine the quality of data and whether the De-trended result can be used or thrown out.

For equation 1.1, we are going to discuss the derivation of v' and how the Least Squares or Cspline fit of this curve is critical to producing an accurate De-trended result. Upon integration of the original Acceleration-Time history, if the resulting velocity curve tends toward infinity then De-trending is necessary to remove the unwanted distortions in the signal. The resulting velocity curve may start out on a linear trend and then deform into a parabolic arc (Fig. 1.1) or it may shift about a linear trend line and dampen out about the line as it approaches infinity (Fig. 1.2). In either case, we need to compute an accurate representation of the velocity curve.

The technique we are going to use is a combination Linear fit and Cspline approach. The linear fit is performed with a least-squares method until a 2-sigma value is reached. From that point, a cubic spline

or Cspline is used. The Cspline is "seeded" with points from a Savitzky-Golay smoothing filter of order 0 which is a moving average. This technique was implemented in a MatLab like program called "CAM". "CAM" is powerful proprietary software written in-house by the Structural Dynamics group at Kennedy Space Center. You can see in figure (1.1) the green circles that represent the seed points on the curve. The black linear line from 0 to .008sec is the Least Squares fit and the parabolic black curve is the Cspline fit based on the Savitzky-Golay seeds or moving average smoothing filter. Although the data presented in this figure is bad and cannot be used due to extreme velocity shifts and fluctuations, you can see how the combination of Savitzky-Golay smoothing function and Cspline fit contribute to create a smooth curve based on erratic data fluctuations.

De-trending Examples:

The following examples illustrate the effects of De-trending. In the case of Figures 1.1 & 1.2, extreme instantaneous velocity shifts are noted where the Velocity De-trending technique cannot correct these problems and therefore the data is invalid and needs to be discarded. In figures (1.3 & 1.4), the Raw acceleration is zero shifted below the horizontal axis and the resultant De-trended acceleration is symmetric about the zero axis and exhibits a more uniform decay in time. For figures (1.5 & 1.6), you can see the effect on velocity from the original curve v , to the De-trended Velocity v'' . The De-trended velocity curve now decays as a sinusoid about zero rather than tending toward infinity.

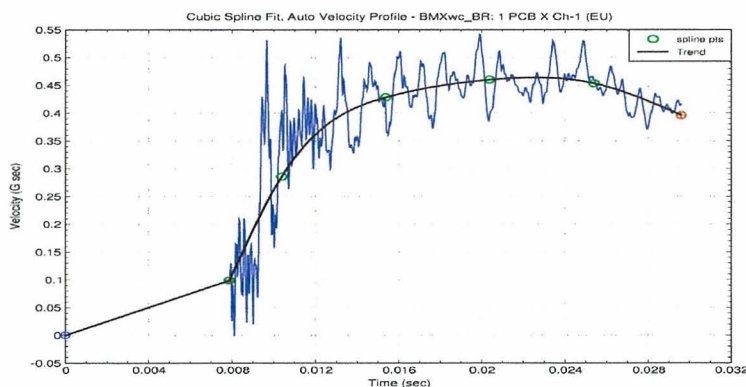


Figure (1.1)

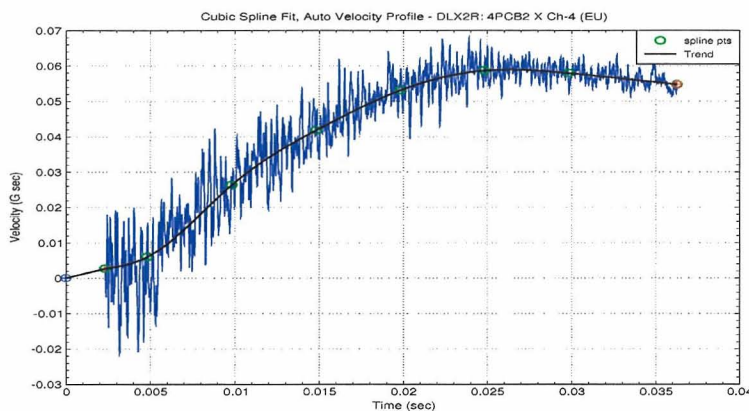


Figure (1.2)

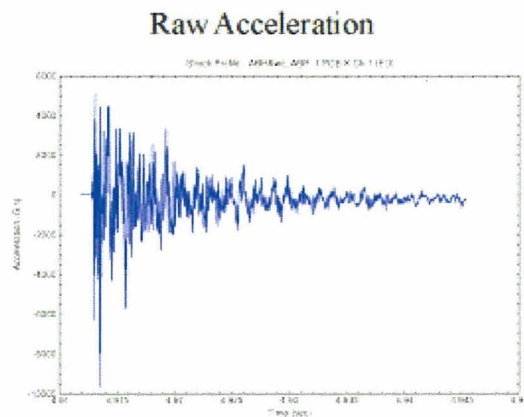


Figure (1.3)

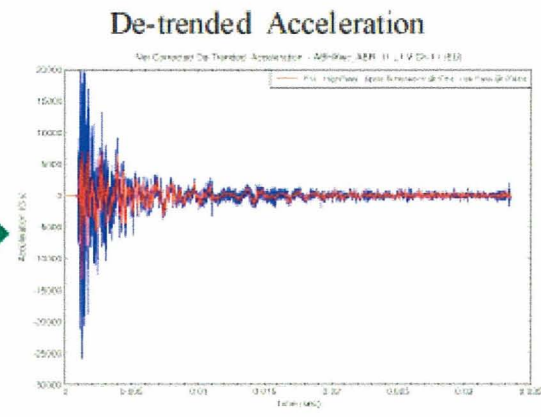


Figure (1.4)

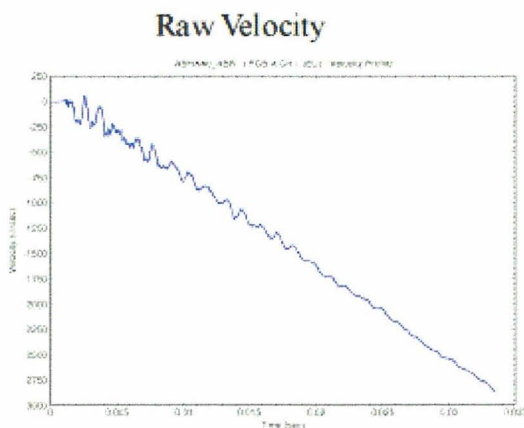


Figure (1.5)

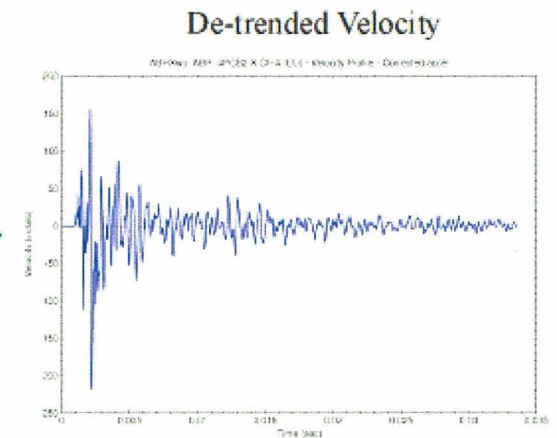
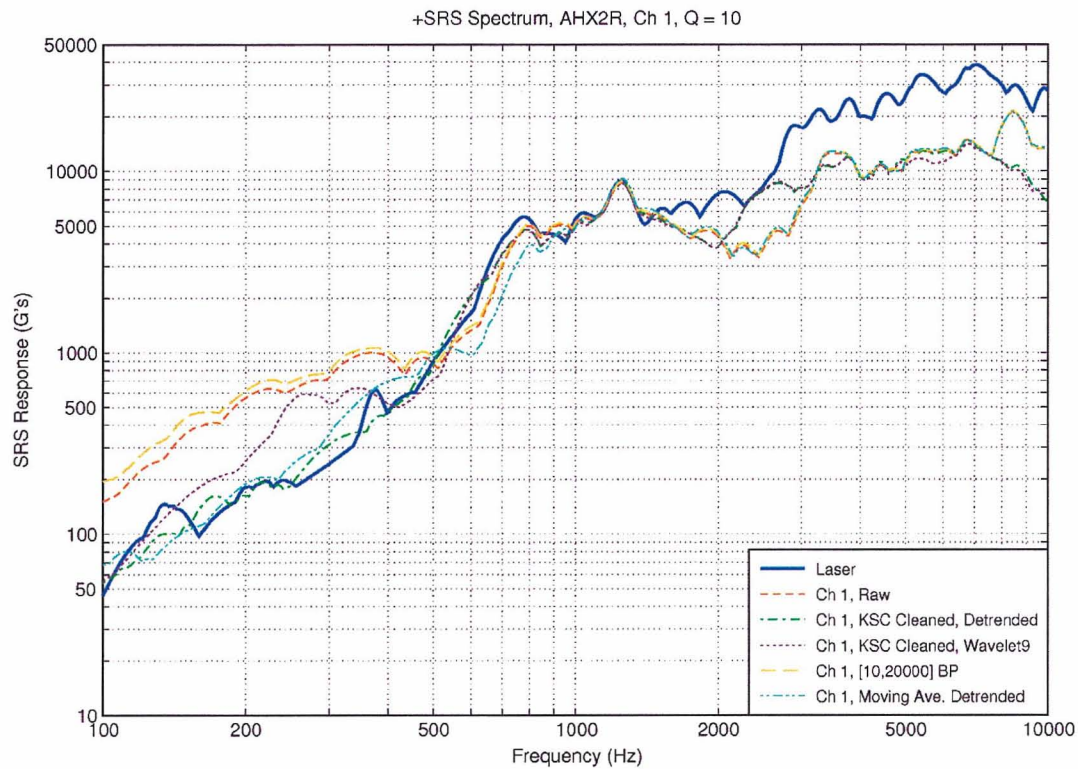


Figure (1.6)

As previously mentioned for the data in figures (1.1 & 1.2), De-trending would not correct the deficiencies in the signal as demonstrated in the examples given in Figures (1.4 & 1.6). The data would have to be discarded and a new test performed insuring that the root cause of the deficiencies was understood and corrected.

Other De-trending techniques can be used to illuminate the quality of shock data and provide a method for comparing data and understanding the true environment. Figure (1.7) illustrates a comparison of various techniques including: Wavelet, Velocity, BandPass & Moving Average methods. The reference or "Truth Data" environment used in this example was the signal from a Laser Vibrometer. The Laser Vibrometer is one of the most accurate instruments used to measure high level shock data. Laser Vibrometers use the Doppler effect to provide a Laser signal that is reflected from a reference mirror on the test specimen to the pickup sensor. This provides an extremely high level of response where effective scans rates can be on the order of many magnitudes of the Nyquist frequency or in excess of 1.2 million samples per second. In Figure (1.7), you can see that KSC Velocity De-trending provides a very accurate method for De-trending data compared to the Laser Vibrometer results. You will also

notice some of the other methods including BandPass and Wavelet9 are not very robust especially at lower frequencies in range of (100-500Hz). For frequencies above 2000Hz, all of the methods tend to diverge from the Laser Vibrometer results which is due to test setup and fixture effects including structural natural frequencies.

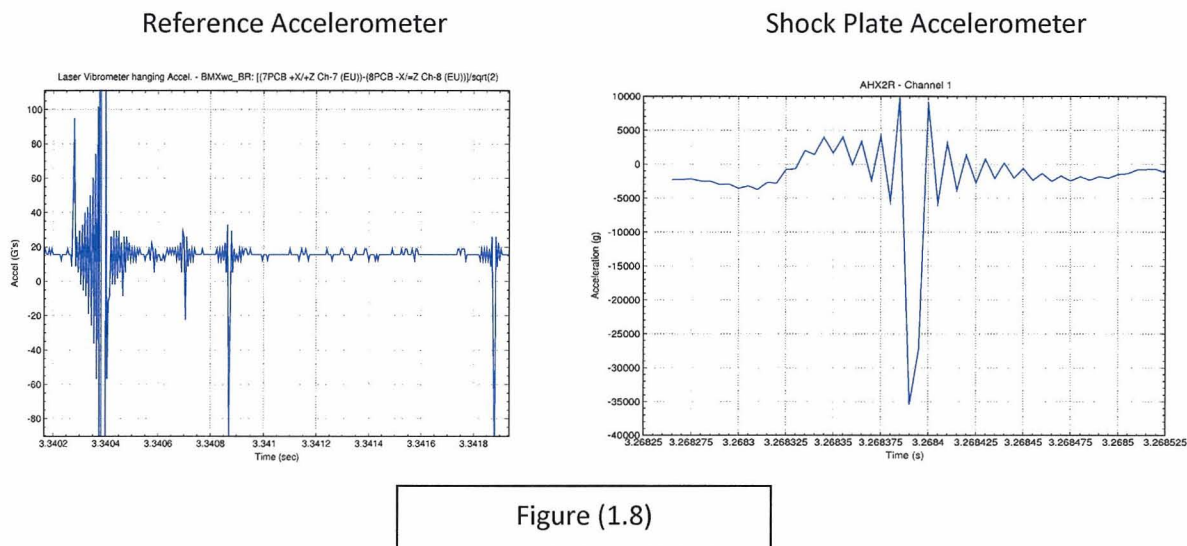


Signal Deficiencies:

As we touched on in the previous section, an important part of analyzing shock data is understanding the root cause of signal deficiencies. There are many causes of signal deficiencies in Shock testing and analysis which include both pre-test setup and configuration along with post-test data acquisition.

For pre-test configuration; improper grounding, loose or improperly bonded Accelerometers, signal circuit noise, EMI/EMR radiation induction effects and improperly conditioned Power or electrical noise in the power supply to the lab can all effect results. Improper grounding can generate significant signal noise and have a profound effect on results by displacing the Shock Response Spectrum (SRS) well above the true levles. Figure (1.8) represents a 100KHz noise signature that was over 35,000Gs for a duration less than 100micro seconds. The noise resulted from poor gounding between the Shock plate and the the Piezoelectric accelerometer. The noise was proven to displace The SRS curve by (8 - 12dB) in the

frequency band from (100-2000Hz) which acted to overstate the results of shock testing in this frequency band. Another area of concern is noisy or ill-conditioned power coming into the Lab. This can result in large noise spikes in the data at (50-60)Hz which will effect the SRS results.



For post-test data acquisition; equivalent RC circuit gain response and circuit saturation (Slew Rate Limited) can all effect results. In this case, the accelerometer may not be sized properly where the max. response of the accelerometer is 5,000Gs and the actual shock is on the order of 50,000Gs. The data acquisition system cannot sample at a high enough rate where the sampling rate should be at least (2 x Nyquist) frequency. The Nyquist frequency is defined as the minimum frequency for accurate signal reconstruction and the sampling rate is defined as twice the Nyquist frequency. For example, if you are measuring high level shock out to 10,000hz, the sampling rate should be at least 20KHz and in reality on the order of (100-200KHz).

There are many causes of signal deficiencies including: DC shifts, improper AC coupling, Circuit noise including EMI/EMR, Equivalent RC circuit gain response, circuit saturation or “Slew Rate Limited”, fixture grounding and wiring losses. All of these factors can contribute to bad shock data being recorded and numerous retests. The key point is a re-test will not help if there is a systemic problem in the Pre-test or Post-test systems. The problems must be addressed and resolved before testing is allowed to continue. Laser Vibrometers provide a significant advantage over Piezoelectric or Piezoresistive accelerometer for shock testing, but are not widely used due to initial cost.

Conclusion:

To summarize, the Velocity De-trending technique presented provides a powerful method to pre-screen and clean Shock testing results and determine if the data being recorded accurately represents the “Truth Data”. Not all zero shifted acceleration Shock data can be De-trended using the methods

described in this paper. Some data that is zero-shifted or exhibits large instantaneous velocity shifts is inherently bad and a retest is warranted. Acceleration-Time history data that looks normal upon visual inspection can be bad upon examining the Velocity and displacement results. Some data can be De-trended or cleaned without being inherently bad whereas other data has to be discarded. It is important that Engineering Shock Test Labs employ a method to De-trend or Pre-screen Shock test data to ensure the quality of results. Without pre-screening the Shock testing environment, significant time and money will be wasted by the test Lab. De-trending is one tool available to ensure the quality of shock testing results, but Engineering judgement and experience will ultimately determine the validity of Shock data.

References :

[1] Title: Why Shock Measurements Performed at Different Facilities Don't Agree

Author: Roy Melander, Strether Smith

Source: Proceedings, Shock & Vibration Symposium October 1995

[2] Title: IES Recommended Practice 012.1 - Handbook for Dynamic Data Acquisition and Analysis

Author: Harry Himmelblau, Allan G. Piersol, James H. Wise, Max R. Grundvig

Source: Institute of Environmental Sciences, 940 East Northwest Highway, Mount prospect, IL 60056, Tel: 708-255-1561, Fax: 708-255-1699

Abstract:

1) Scope of Problem:

- Can we believe results from Pyroshock testing?
- Pyroshock Testing results can vary widely between facilities.
- Why clean questionable shock data?
 - True levels, "Truth Data".
 - Re-testing may be impractical, expensive and affect schedule.
- Under testing and Over testing of components can result in the following:
 - Not meeting Qualification requirements.
 - Adding damage which may break the component

2) Methods/procedure/approach:

- Develop pyroshock De-trending technique to clean questionable data.
- De-trending technique developed using a Velocity based method.
 - Compute Least Squares & Cspline Curve Fit of Velocity using selected time range. Technique uses combination Least Squares, Savitzky-Golay and Cspline function to fit Velocity profile. The result is then subtracted from original curve.
- Expand technique to determine the validity of data.
- Compare De-trended data to original data and make an assessment.

3) Results/findings/product:

- De-trending technique is highly dependent on the quality of data.
- De-trending cannot correct data that is inherently bad.
- De-trending can correct issues such as DC shifts and circuit saturation such as Slew Rate limitations.
- Laser Vibrometers provide superior performance and reliability compared to pyroshock accelerometers

4) Conclusion/implications:

- Not all zero shifted acceleration data can be De-trended using this technique.
- DC Shifts, improper AC coupling, Circuit noise/EMI/EMR, Equivalent RC circuit gain response/Circuit saturation (Slew Rate Limited), fixture grounding and wiring losses can all contribute to bad shock data being recorded.
- Some data that is zero-shifted or exhibit large instantaneous velocity shifts is inherently bad and a retest is warranted.
- Clean Acceleration-Time history data can be bad upon examining the Velocity & Displacement profiles.
- Laser Vibrometers provide a high level of accuracy for pyrotechnic shock testing.
- Engineering judgment and experience will determine the validity of Shock data.



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De-trending Techniques: Methods For Cleaning Questionable Shock Data

NASA Environments TIM

June 7, 2010

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Dynamic Environments, KSC LSP Flight Analysis Division



Overview

- Scope of the problem?
 - Shock Testing results can vary widely between facilities
 - Under testing and Over testing of components can result in
 - Not meeting Qualification requirements
 - Adding damage which may break the component
- Type of Shock Data
 - High level pyrotechnic Shock, typically greater than 1000 Gs.
- Why clean questionable shock data?
 - True levels, "Truth Data"
 - Data reviewed after-the-fact
 - Re-testing may be impractical, expensive, and affect schedule.
- How do we know if data is suspect?



Shock Testing Best Practices

IES "Handbook for Dynamic data Acquisition & Analysis – ver. 12.1"

- Accelerometers should not be closer than 6in to pyrotechnic source.
- A zero shift in acceleration data may be an indication of invalid data or improper test setup.
- Velocity should not diverge to infinity, but rather oscillate around zero and dampen out.
- Displacement should not diverge to infinity.
- Acceleration-Time histories should be centered about zero and not exhibit Noise spikes or zero shifts.
- Negative and Positive SRS data should look similar.



De-trending Methods

- Velocity method
 - Least Squares or Cspline fit of Velocity curve is derived and subtracted from the original Acceleration-Time history.
- Displacement method
 - Least Squares or Cspline fit of Displacement curve is derived and subtracted from the original Acceleration-Time history.
- Wavelet
 - Uses the Daubechies Order-coefficient wavelet filter to remove the highest and lowest frequency components of signal.
- Bandpass filter (4-pole Butterworth) between 10Hz and 20 KHz.
- Moving Average Cspline fit with bandpass filter



CAM De-trending Technique

- Compute Least Squares & Cspline Curve Fit of Velocity using selected time range.
- Use combination Least Squares ,Savitzky-Golay and Cspline function to fit Velocity profile.
- Compute De-trended Acceleration Shock Curve
- Subtract Normalized Acceleration curve from original Acceleration Curve

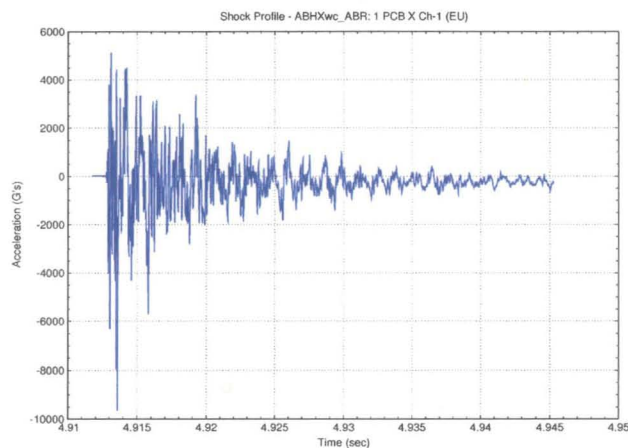


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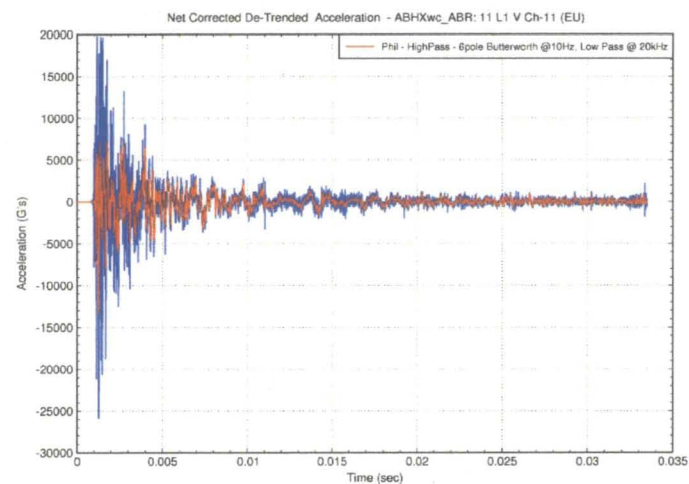
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Examples: Effects of De-trending

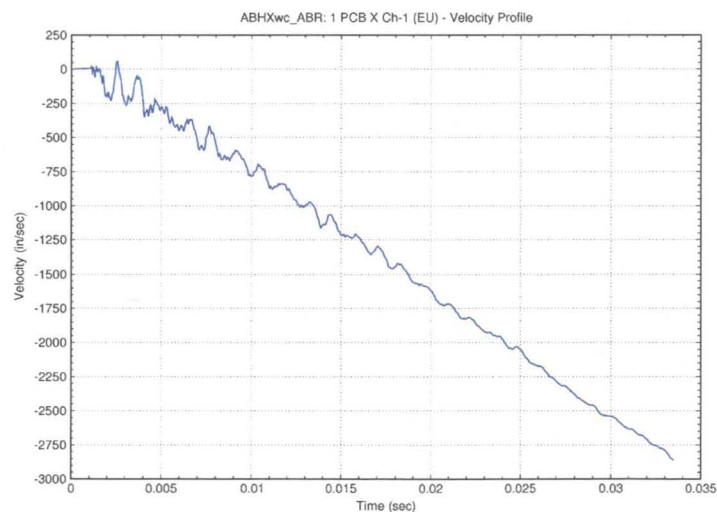
Raw Acceleration



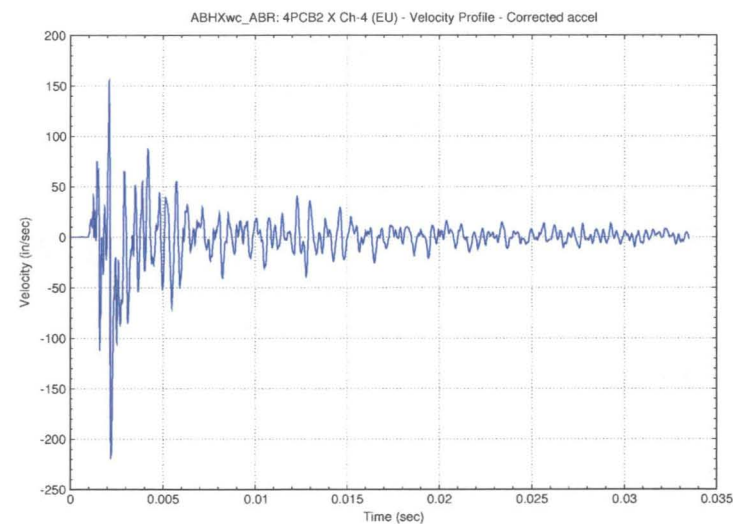
De-trended Acceleration



Raw Velocity



De-trended Velocity



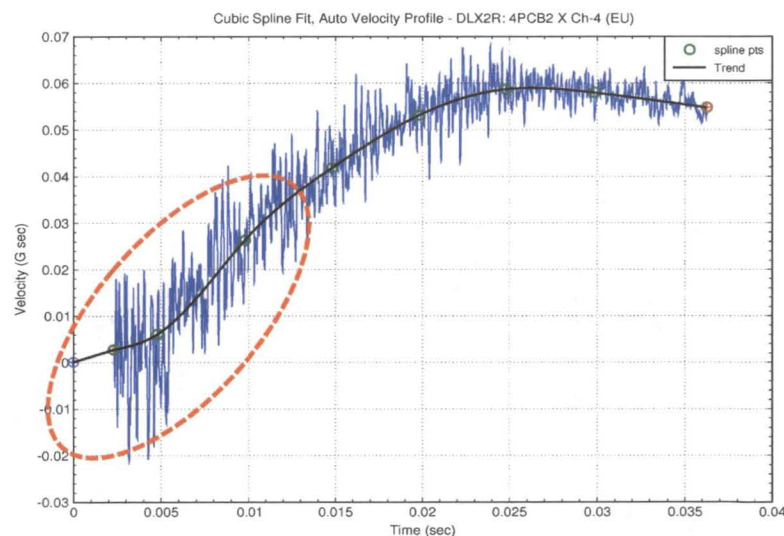
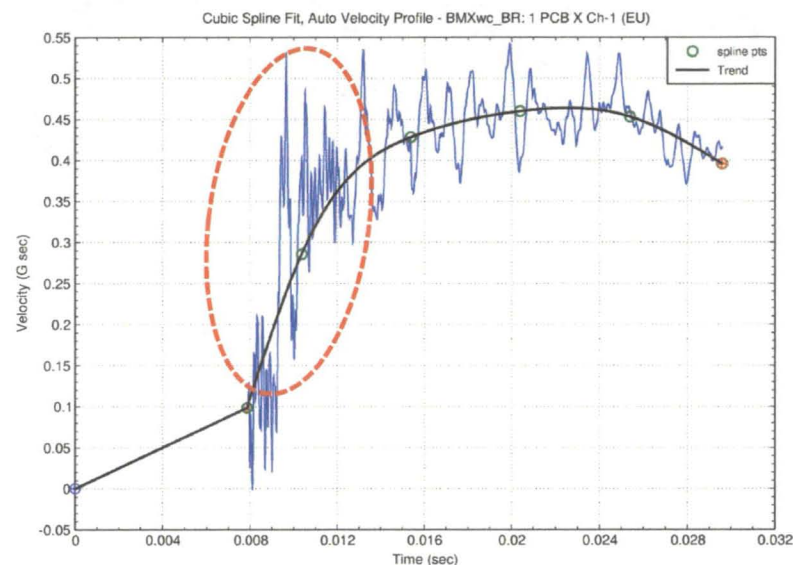


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Examples of Bad Data – De-trended Velocity

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- Accel data quality
 - Instantaneous velocity shifts noted in several data sets
 - De-trending technique does not correct for errors and indicates bad data.
 - Results from bad accelerometer SRS compared to laser Vibrometer SRS.
 - Data with this signature should be thrown out as invalid.



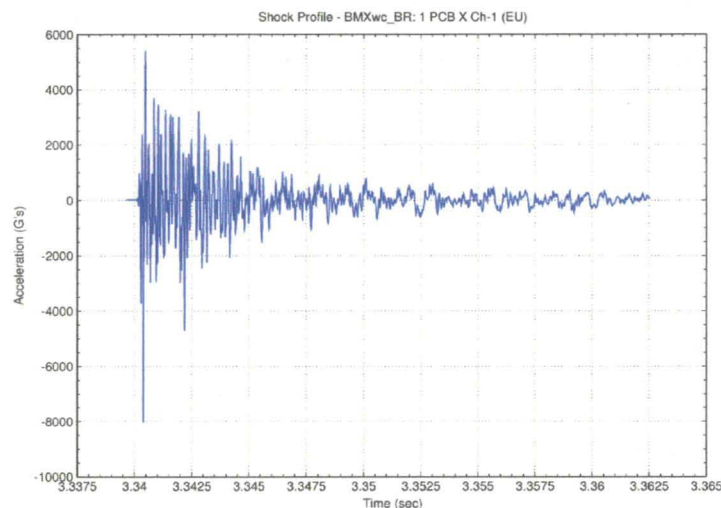


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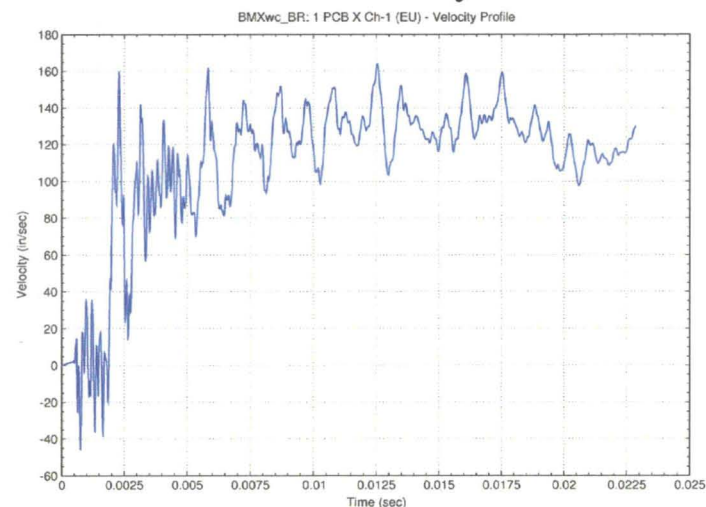
Examples of Bad Data - Accel./Vel./Disp.

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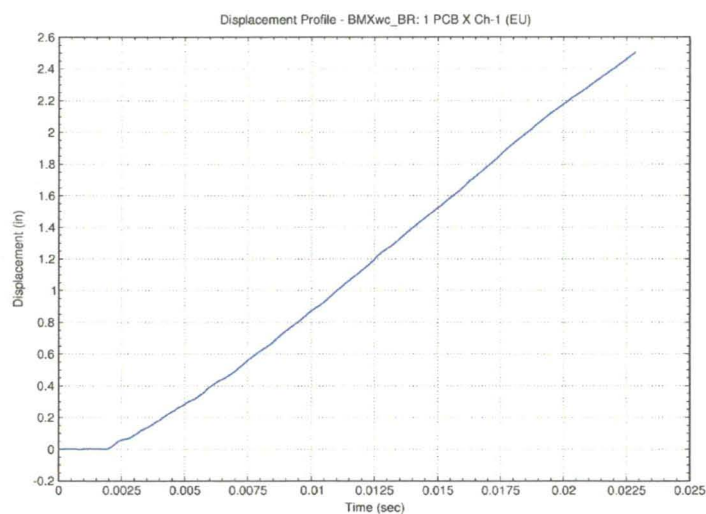
Raw Acceleration



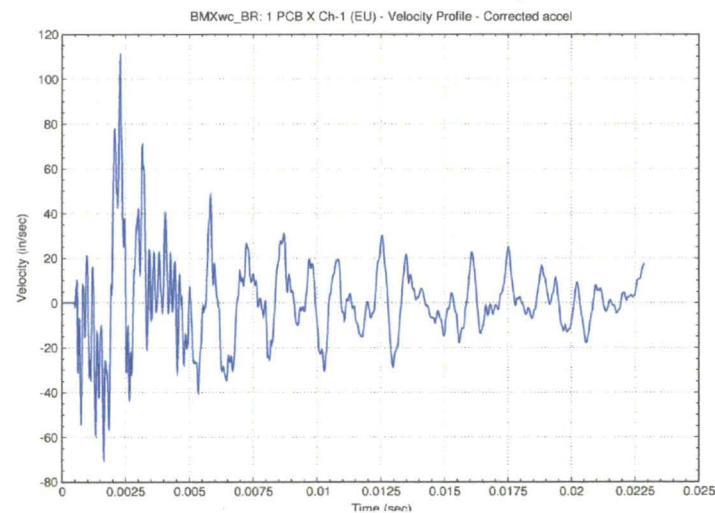
Raw Velocity



Raw Displacement



De-trended Velocity

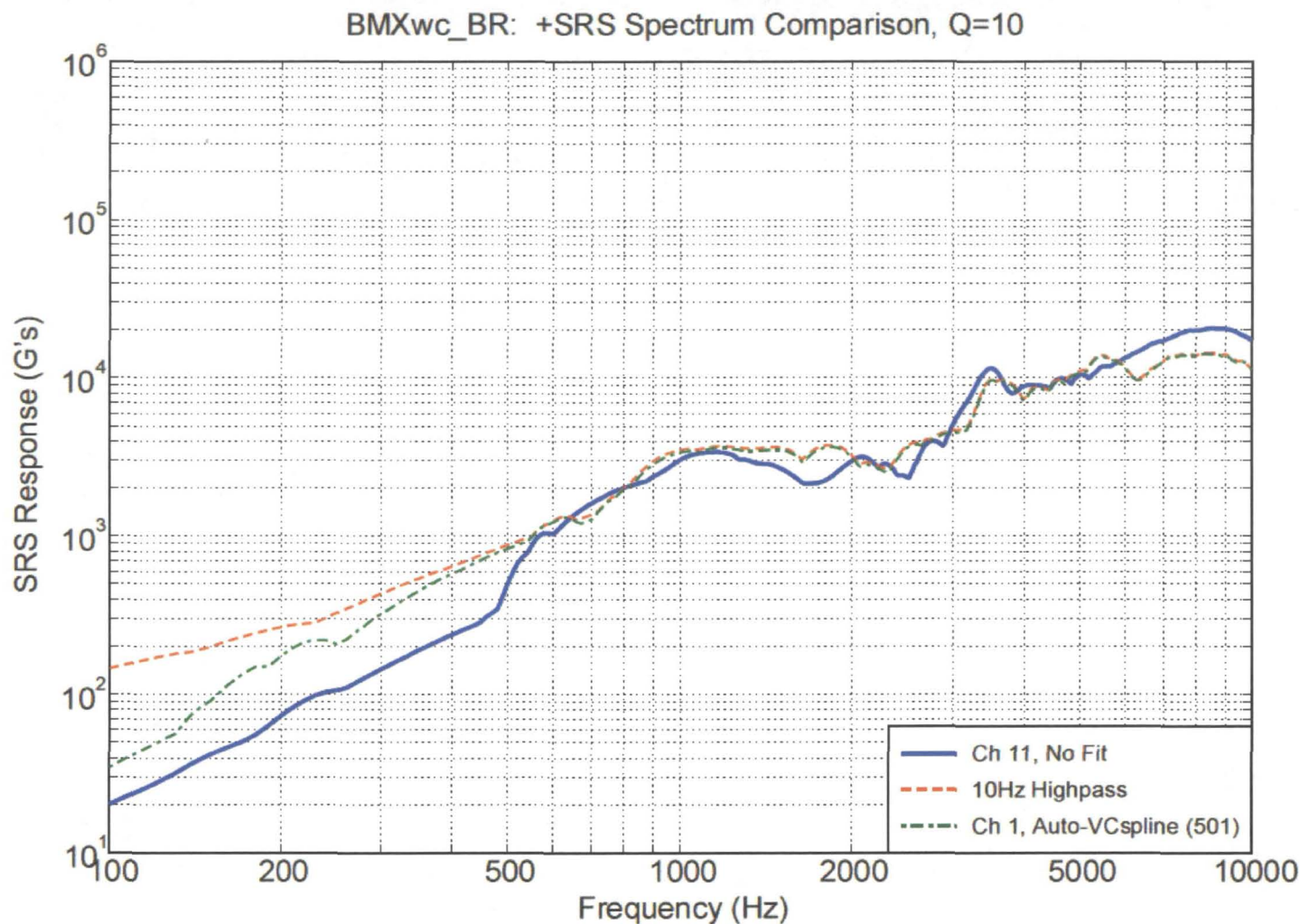




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Example of Bad Data – De-trended SRS compared to Laser Vibrometer channel

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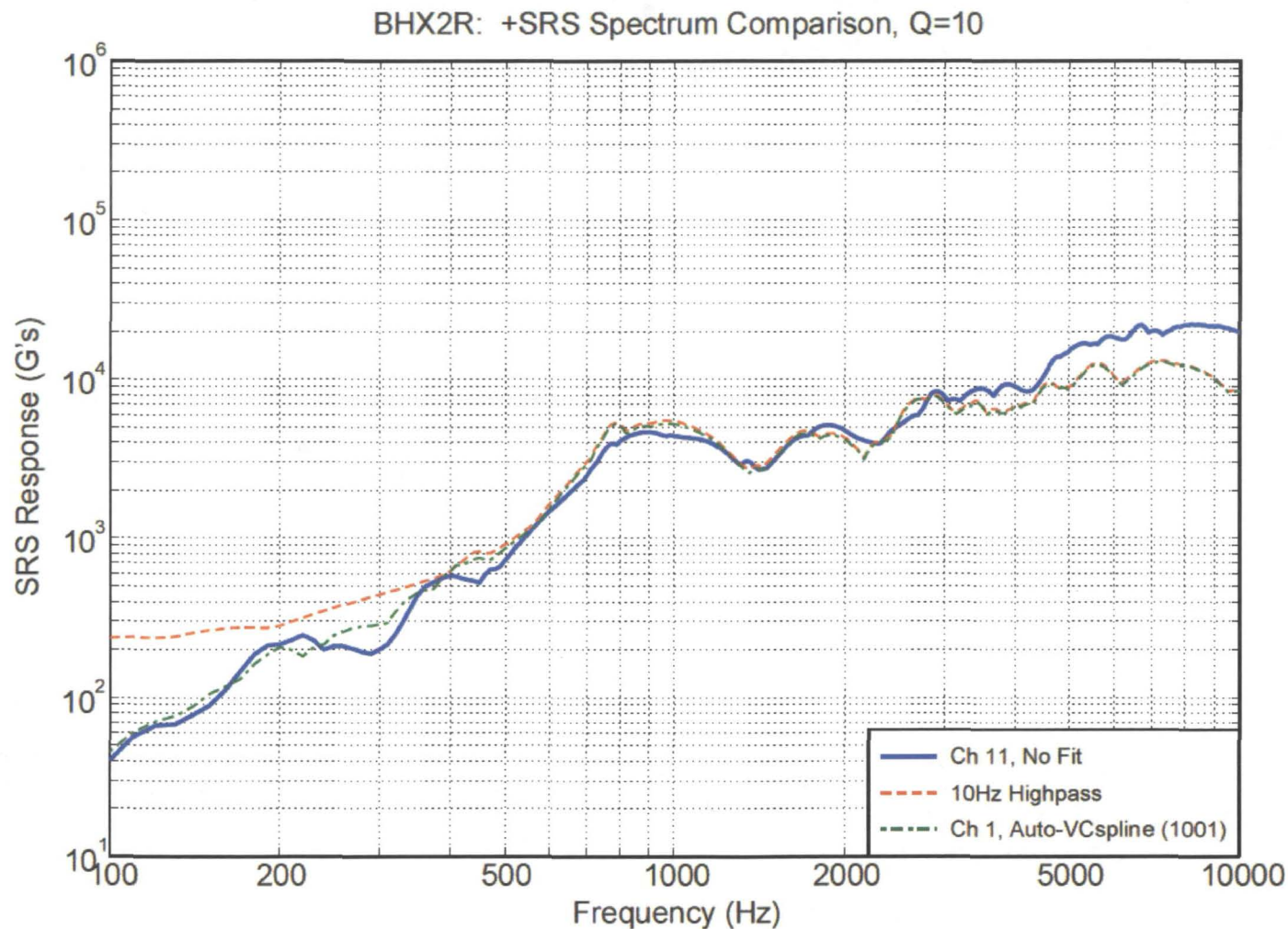




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Example of Good Data - Detrended SRS compared to Laser Vibrometer channel

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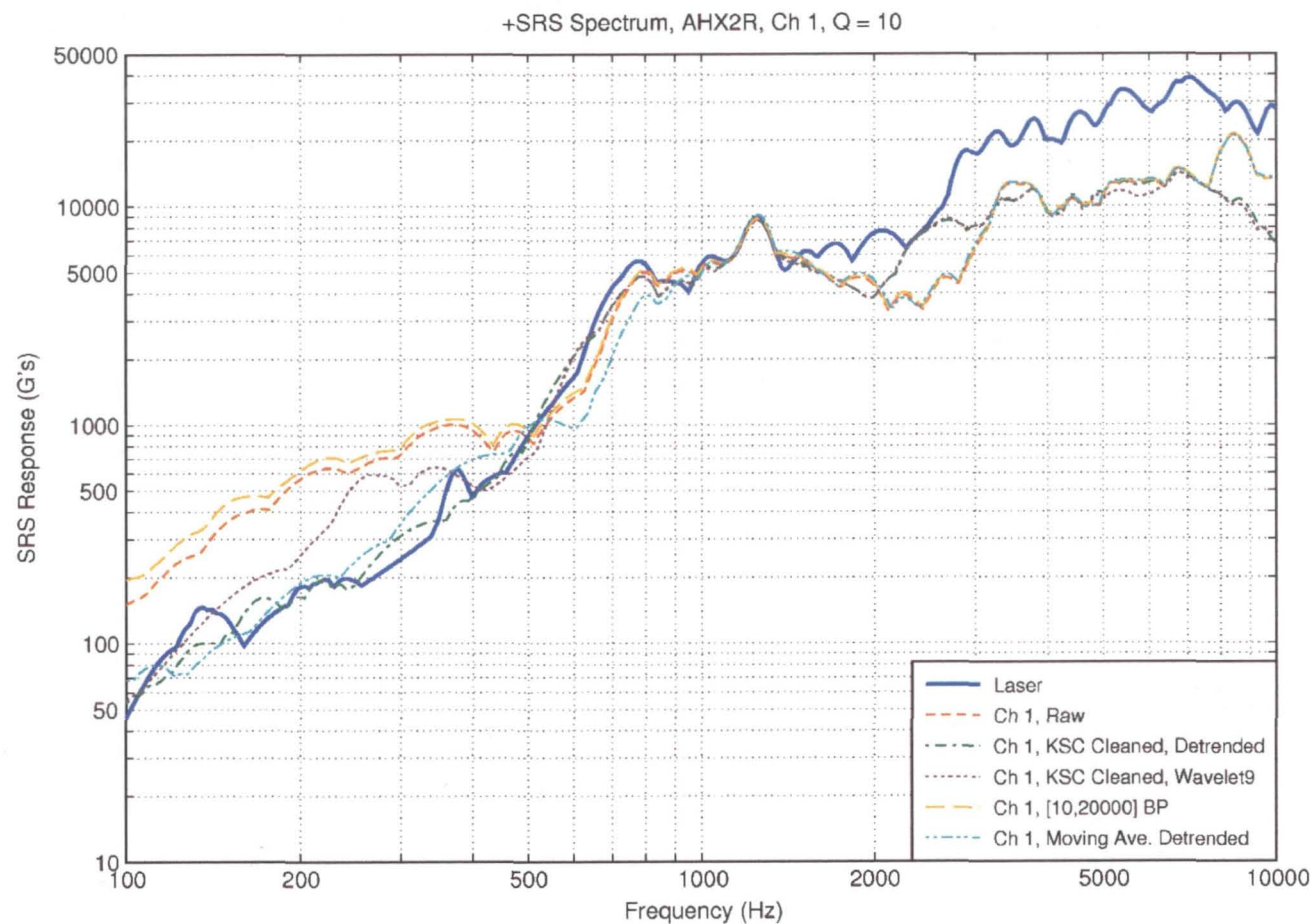




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Other De-trending techniques: Wavelet & Moving Ave/Cspline methods

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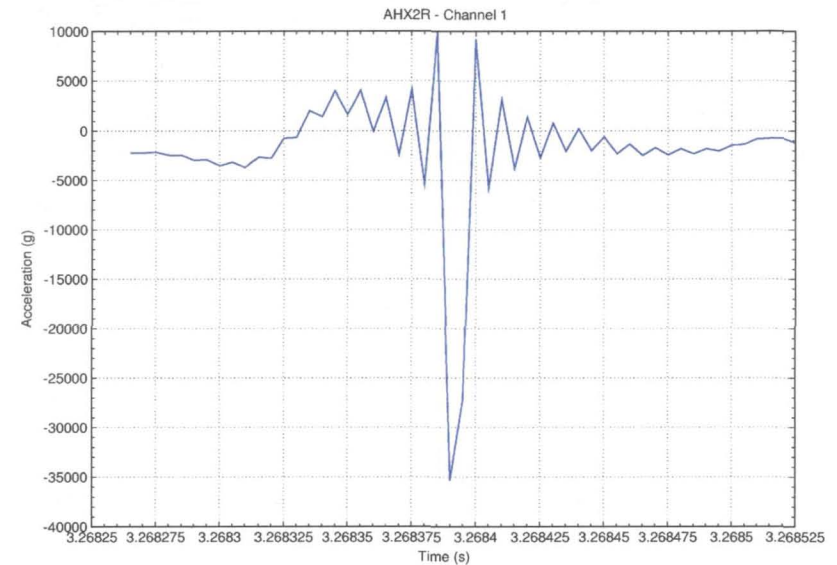


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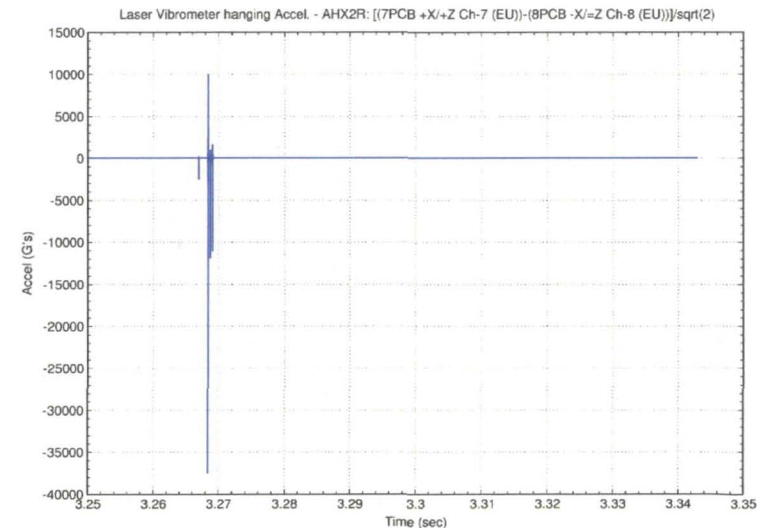
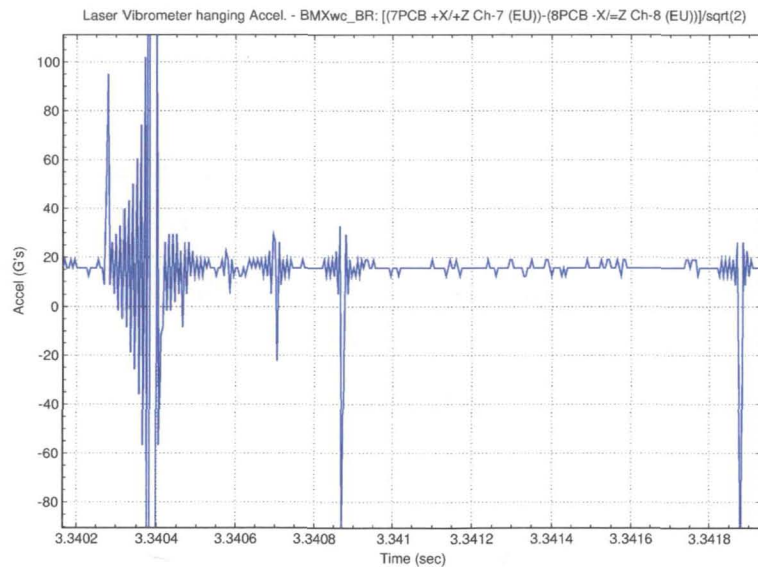
Noise Spikes and Data Quality

- Noise spikes listed have 100 KHz 'signature'
- Noise proven to displace SRS curve significantly even though the time duration was less than 100micro seconds.
- Source was determined to be poor grounding between Vibration Plate and Accelerometer.

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Laser Vibrometer reference





Conclusions

- Not all zero shifted acceleration data can De-trended using this technique.
- DC shifts, improper AC coupling, Circuit noise/EMI/EMR, Equivalent RC circuit gain response/Circuit saturation(Slew Rate Limited), fixture grounding and wiring losses can all contribute to bad shock data being recorded.
- Some data that is zero-shifted or exhibit large instantaneous velocity shifts is inherently bad and a retest is warranted.
- Clean Acceleration-Time history data can be bad upon examining the Velocity & Displacement profiles.
- Laser Vibrometers provide a high level of accuracy for pyrotechnic shock testing.
- Engineering judgment and experience will determine the validity of Shock data.